

Introduction, and a Short History of the Second Law of Thermodynamics

In this chapter, I shall present some important milestones in the history of the Second Law of Thermodynamics. I shall also present a few formulations of the Second Law in a descriptive manner. In doing so, I necessarily sacrifice precision. The important point here is not to teach you the Second Law, but to give you a qualitative description of the types of phenomena which led the scientists of the nineteenth century to formulate the Second Law.

There are many formulations of the Second Law of Thermodynamics. We shall group all these into two conceptually different classes: Non-Atomistic and Atomistic.

1.1. The *Non-Atomistic* Formulation of the Second Law¹

Traditionally, the birth of the Second Law is associated with the name Sadi Carnot (1796–1832). Although Carnot himself did

¹By “non-atomistic” formulation, I mean the discussion of the Second Law without any reference to the atomic constituency of matter. Sometimes, it is also said that this formulation views matter as a continuum. The important point to stress here is that these formulations use only macroscopically observable or measurable quantities without any reference to the atomic constituency of matter. It *does not* imply that the formulation applies to non-atomistic or continuous matter. As we shall see later, were matter really non-atomistic or continuous, the Second Law would not have existed.

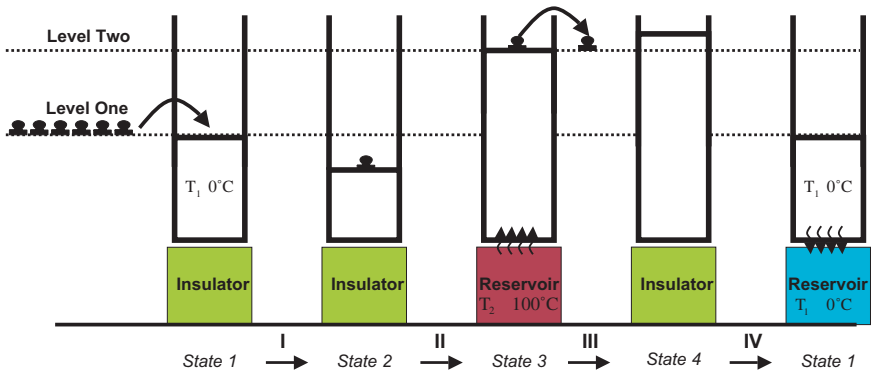


Fig. (1.1) Heat engine.

not formulate the Second Law,² his work laid the foundations on which the Second Law was formulated a few years later by Clausius and Kelvin.

Carnot was interested in heat engines, more specifically, in the efficiency of heat engines. Let me describe the simplest of such an engine (Fig. (1.1)). Suppose you have a vessel of volume V containing any fluid, a gas or a liquid. The upper part of the vessel is sealed by a movable piston. This system is referred to as a heat engine. The vessel is initially in State 1, thermally insulated, and has a temperature T_1 , say 0°C . In the first step of the operation of this engine (Step I), we place a weight on the piston. The gas will be compressed somewhat. The new state is State 2. Next, we attach the vessel to a heat reservoir (Step II). The heat reservoir is simply a very large body at a constant temperature, say $T_2 = 100^\circ\text{C}$. When the vessel is attached to the heat reservoir, thermal energy will flow from the heat reservoir to the engine. For simplicity, we assume that the heat reservoir is immense compared with the size of the system or the engine. In Fig. (1.1), the heat reservoir is shown only at the bottom of the engine. Actually it should surround the entire engine. This

²This is the majority opinion. Some authors do refer to Carnot as the “inventor” or the “discoverer” of the Second Law.

ensures that after equilibrium is reached, the system will have the same temperature, T_2 , as that of the reservoir, and though the reservoir has “lost” some energy, its temperature will be nearly unchanged. As the gas (or the liquid) in the engine heats up, it expands, thereby pushing the movable piston upwards. At this step, the engine did some useful work: lifting a weight placed on the piston from level one to a higher level, two. The new state is State 3. Up to this point, the engine has absorbed some quantity of energy in the form of heat that was transferred from the reservoir to the gas, thereby enabling the engine to do some work by lifting the weight (which in turn could rotate the wheels of a train, or produce electricity, etc.). Removing the weight, Step III, might cause a further expansion of the gas. The final state is State 4.

If we want to convert this device into an engine that repeatedly does useful work, like lifting weights (from level one to level two), we need to operate it in a complete cycle. To do this, we need to bring the system back to its initial state, i.e., cool the engine to its initial temperature T_1 . This can be achieved by attaching the vessel to a heat reservoir or to a thermostat, at temperature $T_1 = 0^\circ\text{C}$, Step IV (again, we assume that the heat reservoir is much larger compared with our system such that its temperature is nearly unaffected while it is attached to the engine). The engine will cool to its initial temperature T_1 , and if we take away the weight, we shall return to the initial state and the cycle can start again.

This is not the so-called Carnot cycle. Nevertheless, it has all the elements of a heat engine, doing work by operating between the two temperatures, T_1 and T_2 .

The net effect of the repeated cycles is that heat, or thermal energy, is pumped into the engine from a body at a high temperature $T_2 = 100^\circ\text{C}$; work is done by lifting a weight and another amount of thermal energy is pumped out from the engine into a body at lower temperature $T_1 = 0^\circ\text{C}$. The Carnot

cycle is different in some details. The most important difference is that all the processes are done very gradually and very slowly.³ We shall not be interested in these details here.

Carnot was interested in the *efficiency* of such an engine operating between two temperatures under some ideal conditions (e.g. mass-less piston, no friction, no heat loss, etc.).

At the time of the publication of Carnot's work in 1824,⁴ it was believed that heat is a kind of fluid referred to as *caloric*. Carnot was mainly interested in the limits on the efficiency of heat engines. He found out that the limiting efficiency depends only on the ratio of the temperatures between which the engine operates, and not on the substance (i.e., which gas or liquid) that is used in the engine. Later, it was shown that the efficiency of Carnot's idealized engine could not be surpassed by any other engine. This laid the cornerstone for the formulation of the Second Law and paved the way for the appearance of the new term "entropy."

It was William Thomson (1824–1907), later known as Lord Kelvin, who first formulated the Second Law of Thermodynamics. Basically, Kelvin's formulation states that there could be no engine, which when operating in cycles, the *sole* effect of which is pumping energy from one reservoir of heat and completely converting it into work.

Although such an engine would not have contradicted the First Law of Thermodynamics (the law of conservation of the total energy), it did impose a limitation on the amount of work that can be done by operating an engine between two heat reservoirs at different temperatures.

³Technically, the processes are said to be carried out in a quasi-static manner. Sometimes, this is also referred to as a reversible process. The latter term is, however, also used for another type of process where entropy does not change. Therefore, the term quasi-static process is more appropriate and preferable.

⁴"Reflections on the motive power of fire and on machines fitted to develop this power," by Sadi Carnot (1824).

In simple terms, recognizing that heat is a form of energy, the Second Law of Thermodynamics is a statement that it is impossible to convert heat (thermal energy) completely into work (though the other way is possible, i.e., work can be converted completely into heat, for example, stirring of a fluid by a magnetic stirrer, or mechanically turning a wheel in a fluid). This impossibility is sometimes stated as “a perpetual motion of the second kind is impossible.” If such a “perpetual motion” was possible, one could use the huge reservoir of thermal energy of the oceans to propel a ship, leaving a tail of slightly cooler water behind it. Unfortunately, this is impossible.

Another formulation of the Second Law of Thermodynamics was later given by Rudolf Clausius (1822–1888). Basically, Clausius’ formulation is what every one of us has observed; heat always flows from a body at a high temperature (hence is cooled) to a body at a lower temperature (which is heated up). We never observe the reverse of this process occurring spontaneously. Clausius’ formulation states that no process exists, such that its net effect is only the transfer of heat from a cold to a hot body. Of course we can achieve this direction of heat flow by doing work on the fluid (which is how refrigeration is achieved). What Clausius claimed was that the process of heat transferred from a hot to a cold body when brought in contact, which we observe to occur spontaneously, can never be observed in the reverse direction. This is shown schematically in Fig. (1.2), where two bodies initially isolated are brought into thermal contact.

While the two formulations of Kelvin and Clausius are different, they are in fact equivalent. This is not immediately apparent.



Fig. (1.2)

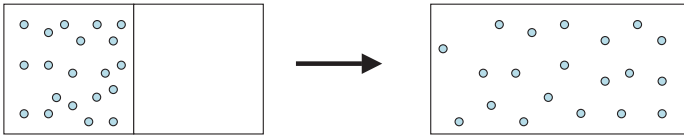


Fig. (1.3)

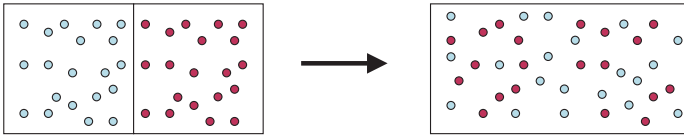


Fig. (1.4)

However, a simple argument can be employed to prove their equivalency, as any elementary textbook of thermodynamics will show.

There are many other formulations or manifestations of the Second Law of Thermodynamics. For instance, a gas in a confined volume V , if allowed to expand by removing the partition, will always proceed in one direction (Fig. (1.3)).⁵ The gas will expand to fill the entire new volume, say $2V$. We never see a spontaneous reversal of this process, i.e., gas occupying volume $2V$ will never spontaneously converge to occupy a smaller volume, say V .

There are more processes which all of us are familiar with, which proceed in one way, never in the reverse direction, such as the processes depicted in Figs. (1.2), (1.3), (1.4) and (1.5). Heat flows from a high to a low temperature; material flows from a high to a low concentration; two gases mix spontaneously; and a small amount of colored ink dropped into a glass of water will spontaneously mix with the liquid until the water

⁵The Second Law may also be formulated in terms of the spontaneous expansion of a gas. It can also be shown that this, as well as other formulations, is equivalent to the Clausius and Kelvin formulations.

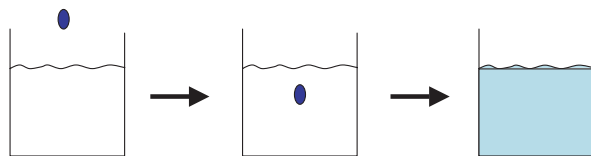


Fig. (1.5)

is homogeneously colored (Fig. (1.5)). We never see the reverse of these processes.

All these processes have one thing in common. They proceed in one direction, never proceeding *spontaneously* in the reverse direction. But it is far from clear that all these processes are driven by a common law of nature. It was Clausius who saw the general principle that is common in all these processes. Recall that Clausius' formulation of the Second Law is nothing but a statement of what everyone of us is familiar with. The greatness of Clausius' achievement was his outstanding prescience that all of these spontaneous processes are governed by one law, and that there is one quantity that governs the direction of the unfolding of events, a quantity that always changes in one direction in a spontaneous process. This was likened to a one-way arrow or a vector that is directed in one direction along the time axis. Clausius introduced the new term *entropy*. In choosing the word "entropy," Clausius wrote:⁶

"I prefer going to the ancient languages for the names of important scientific quantities, so that they mean the same thing in all living tongues. I propose, accordingly, to call S the entropy of a body, after the Greek word 'transformation.' I have designedly coined the word entropy to be similar to energy, for these two quantities are so

⁶Quoted by Cooper (1968).

analogous in their physical significance, that an analogy of denominations seems to me helpful.”

In the Merriam-Webster Collegiate Dictionary (2003), “entropy” is defined as: “change, literary turn, a measure of the unavailable energy in a closed thermodynamic system... a measure of the system’s degree of order...”

As we shall be discussing in Chapter 8, the term *entropy* in the sense that was meant by Clausius is an inadequate term. However, at the time it was coined, the molecular meaning of entropy was not known nor understood. In fact, as we shall see later, “entropy” is not *the* “transformation” (nor the “change” nor the “turn”). It is something else that *transforms* or *changes* or *evolves* in time.

With the new concept of entropy one could proclaim the general overarching formulation of the Second Law. In any spontaneous process occurring in an isolated system, the entropy never decreases. This formulation, which is very general, embracing many processes, sowed the seed of the mystery associated with the concept of entropy, the mystery involving a quantity that does not subscribe to a conservation law.

We are used to conservation laws in physics. This makes sense:⁷ material is not created from nothing, energy is not given to us free. We tend to conceive of a conservation law as “understandable” as something that “makes sense.” But how can a quantity increase indefinitely and why? What fuels that unrelenting, ever-ascending climb? It is not surprising that the Second Law and entropy were shrouded in mystery. Indeed, within the context of the macroscopic theory of matter, the Second Law of Thermodynamics is unexplainable. It could have stayed

⁷Here we use the term “makes sense” in the sense that it is a common *experience* and not necessarily a consequence of logical reasoning.

a mystery forever had the atomic theory of matter not been discovered and gained the acceptance of the scientific community. Thus, with the macroscopic formulation we reach a dead end in our understanding of the Second Law of Thermodynamics.

1.2. The Atomistic Formulation of the Second Law

Before the development of the kinetic theory of heat (which relied on the recognition of the atomistic theory of matter), thermodynamics was applied without any reference to the composition of matter — as if matter were a continuum. Within this approach there was no further interpretation of entropy. That in itself is not unusual. Any law of physics reaches a dead end when we have to accept it as it is, without any further understanding. Furthermore, the Second Law was formulated as an absolute law — entropy *always* increases in a spontaneous process in an isolated system. This is not different from any other law, e.g. Newton’s laws are *always* obeyed — no exceptions.⁸

A huge stride forward in our understanding of entropy and of the Second Law of Thermodynamics, was made possible following Boltzmann’s statistical interpretation of entropy — the famous relationship between entropy and the total number of microstates of a system characterized macroscopically by a given energy, volume, and number of particles. Take a look at the cover illustration or at the picture of Boltzmann’s statue. Ludwig Boltzmann (1844–1906),⁹ along with Maxwell and many others, developed what is now known as the kinetic theory of gases, or the kinetic theory of heat. This not only led to the identification of temperature, which we can feel with

⁸“Always” in the realm of phenomena that were studied at that time, and which are now referred to as classical mechanics.

⁹For a fascinating story of Boltzmann’s biography, see Broda (1983), Lindley (2001), and Cercignani (2003).

our sense of touch, with the motions of the particles constituting matter, but also to the interpretation of entropy in terms of the number of states that are accessible to the system.

The atomistic formulation of entropy was introduced by Boltzmann in two stages. Boltzmann first defined a quantity he denoted as H , and showed that as a result of molecular collisions and a few other assumptions, this quantity always decreases and reaches a minimum at equilibrium. Boltzmann called his theorem “the minimum theorem”, which later became famous as Boltzmann’s *H-theorem* (published in 1872). Furthermore, Boltzmann showed that a system of particles starting with any distribution of molecular velocities will reach thermal equilibrium. At that point, H attains its minimum and the resulting velocity distribution will necessarily be the so-called Maxwell distribution of the velocities (see also Chapter 7).

At that time, the atomistic theory of matter had not yet been established nor universally accepted. Although the idea of the “atom” was in the minds of scientists for over two thousand years, there was no compelling evidence for its existence. Nevertheless, the kinetic theory of heat did explain the pressure and temperature of the gas. But what about entropy, the quantity that Clausius introduced without any reference to the molecular composition of matter?

Boltzmann noticed that his H -quantity behaved similarly to entropy. One needs only to redefine entropy simply as the negative value of H , to get a quantity that always *increases* with time, and that remains constant once the system reaches thermal equilibrium.

Boltzmann’s *H-theorem* drew criticisms not only from people like Ernst Mach (1838–1916) and Wilhelm Ostwald

(1853–1932), who did not believe that atoms existed, but also from his colleagues and close friends.¹⁰

The gist of the criticisms (known as the reversibility objection or the reversibility paradox), is the seeming conflict between the so-called time-reversal¹¹ or time symmetry of the Newtonian's equations of motion, and the time asymmetry of the behavior of Boltzmann's H -quantity. This conflict between the reversibility of the molecular collisions, and the irreversibility of the H -quantity was a profound one, and could not be reconciled. How can one derive a quantity that distinguishes between the past and the future (i.e. always increasing with time), from equations of motions that are indifferent and do not care for the past and future? Newton's equations can be used to predict the evolution of the particles into the past as well as into the future. Woven into the H -Theorem were arguments from both mechanics and probability, one is deterministic and time symmetric, while the other is stochastic and time asymmetric. This conflict seems to consist of a fatal flaw in the Boltzmann H -theorem. It was suspected that either something was wrong with the H -theorem, or perhaps even with the very assumption of the atomistic nature of matter. This was clearly a setback for Boltzmann's H -theorem and perhaps a (temporary) victory for the non-atomists.

Boltzmann's reaction to the reversibility objection was that the H -theorem holds most of the time, but in very rare cases,

¹⁰For instance, Loschmidt wrote in 1876 that the Second Law cannot be a result of purely mechanical principle.

¹¹It should be noted as Greene (2004) emphasized that "time-reversal symmetry" is not about time *itself* being reversed or "running" backwards. Instead, time reversal is concerned with whether events that happen *in* time in one particular temporal order can also happen in the reverse order. A more appropriate phrase might be "*event reversal* or *process reversal*".

it can go the other way, i.e. H might increase, or the entropy might decrease with time.

This was untenable. The (non-atomistic) Second Law of Thermodynamics, like any other laws of physics, was conceived and proclaimed as being absolute — no room for *exceptions*, not even rare exceptions. No one had ever observed violation of the Second Law. As there are no exceptions to Newton's equations of motion,¹² there should be no exceptions to the Second Law, not even in rare cases. The Second Law must be absolute and inviolable. At this stage, there were two seemingly different views of the Second Law. On the one hand, there was the classical, non-atomistic and absolute law as formulated by Clausius and Kelvin encapsulated in the statement that entropy never decreases in an isolated system. On the other hand, there was the atomistic formulation of Boltzmann which claimed that entropy increases “most of the time” but there are exceptions, albeit very rare exceptions. Boltzmann proclaimed that entropy could decrease — that it was not an *impossibility*, but only *improbable*.¹³ However, since all observations seem to support the *absolute* nature of the Second Law, it looked as if Boltzmann suffered a defeat, and along with that, the atomistic view of matter.

In spite of this criticism, Boltzmann did not back down. He reformulated his views on entropy. Instead of the *H-theorem* which had one leg in the field of mechanics, and the other in the realm of probability, Boltzmann anchored both legs firmly on the grounds of probability. This was a radically

¹²Within classical mechanics.

¹³As we shall see in Chapters 7 and 8, the admitted non-absoluteness of the atomists' formulation of the Second Law is, in fact, more absolute than the proclaimed absoluteness of the non-atomists' formulation. On this matter, Poincare commented: “...to see heat pass from a cold body to a warm one, it will not be necessary to have the acute vision, the intelligence, and the dexterity of Maxwell's demon; it will suffice to have a little patience” quoted by Leff and Rex (1990).

new and foreign way of reasoning in physics. Probability, at that time, was not part of physics (it was not even a part of mathematics). Boltzmann proclaimed that entropy, or rather atomistic-entropy, is equal to the logarithm of the total number of arrangements of a system. In this bold new formulation, there were no traces of the equations of motion of the particles. It looks as if it is an ad-hoc new definition of a quantity, devoid of any physics at all, purely a matter of *counting* the number of possibilities, the number of states or the number of configurations. This atomistic entropy had built-in provisions for exceptions, allowing entropy to decrease, albeit with an extremely low probability. At that time, the exceptions allowed by Boltzmann's formulation seemed to *weaken* the validity of his formulation compared with the absolute and inviolable non-atomist formulation of the Second Law. In Chapter 8, I shall return to this point arguing that, in fact, the built-in provision for exceptions strengthens rather than weakens the atomistic formulation.

There seemed to be a state of stagnation as a result of the two irreconcilable views of the Second Law. It was not until the atomic theory of matter had gained full acceptance that the Boltzmann formulation won the upper hand. Unfortunately, this came only after Boltzmann's death in 1906.

A year earlier, a seminal theoretical paper published by Einstein on the Brownian motion provided the lead to the victory of the atomistic view of matter. At first sight, this theory seems to have nothing to do with the Second Law.

Brownian motion was observed by the English botanist Robert Brown (1773–1858). The phenomenon is very simple: tiny particles, such as pollen particles, are observed to move at seemingly random fashion when suspended in water. It was initially believed that this incessant motion was due to some tiny living organism, propelling themselves in the liquid. However,

Brown and others showed later that the same phenomenon occurs with inanimate, inorganic particles, sprinkled into a liquid.

Albert Einstein (1879–1955) was the first to propose a theory for this so-called Brownian motion.¹⁴ Einstein believed in the atomic composition of matter and was also a staunch supporter of Boltzmann.¹⁵ He maintained that if there are very large numbers of atoms or molecules jittering randomly in a liquid, there must also be fluctuations. When tiny particles are immersed in a liquid (tiny compared to macroscopic size, but still large enough compared to the molecular dimensions of the molecules comprising the liquid), they will be “bombarded” randomly by the molecules of the liquid. However, once in a while there will be asymmetries in this bombardment of the suspended particles, as a result of which the tiny particles will be moving one way or the other in a zigzag manner.

In 1905 Einstein published as part of his doctoral dissertation, a theory of these random motions.¹⁶ Once his theory was corroborated by experimentalists [notably by Jean Perrin (1870–1942)], the acceptance of the atomistic view became inevitable. Classical thermodynamics, based on the *continuous* nature of matter, does not have room for fluctuations. Indeed, fluctuations in a macroscopic system are extremely small. That is why we do not observe fluctuation in a macroscopic piece of matter. But with the tiny Brownian particles, the fluctuations

¹⁴It is interesting to note that the founders of the kinetic theory of gases such as Maxwell, Clausius and Boltzmann never published anything to explain the Brownian motion.

¹⁵It is interesting to note that Einstein, who lauded Boltzmann for his probabilistic view of entropy, could not accept the probabilistic interpretation of quantum mechanics.

¹⁶A well-narrated story of Einstein’s theory of Brownian motion may be found in John Rigden (2005). A thorough and authoritative discussion of the theory of Brownian motion, including a historical background, has been published by Robert Mazo (2002).

are magnified and rendered observable. With the acceptance of the atomic composition of matter also came the acceptance of Boltzmann's expression for entropy. It should be noted that this formulation of entropy stood fast and was not affected or modified by the two great revolutions that took place in physics early in the 20th century: quantum mechanics and relativity.¹⁷ The door to understanding entropy was now wide open.

The association of entropy with the number of configurations and probabilities was now unassailable from the point of view of the dynamics of the particles. Yet, it was not easily understood and accepted, especially at the time when probability was still not part of physics.

Almost at the same time that Boltzmann published his views on the Second Law, Willard Gibbs (1839–1903) developed the statistical mechanical theory of matter based on a purely statistical or probabilistic approach. The overwhelming success of Gibbs' approach, though based on probabilistic postulates,¹⁸ has given us the assurance that a system of a very large number of particles, though ultimately governed by the laws of motion, will behave in a random and chaotic manner, and that the laws of probability will prevail.

The mere relationship between entropy and the number of states in a system is not enough to explain the behavior of

¹⁷Perhaps, it should be noted that within the recent theories of black holes, people speak about the "generalized Second Law of Thermodynamics" [Bekenstein (1980)]. It seems to me that this generalization does not affect Boltzmann's formula for the entropy.

¹⁸Today, any book on physics, in particular, statistical mechanics, takes for granted the atomic structure of matter. It is interesting to note in Fowler and Guggenheim's book on *Statistical Thermodynamics* (first published in 1939, and reprinted in 1956), one of the first *assumptions* is: "Assumption 1: The *atomistic constitution of matter*." They add the comment that "Today, this hardly ranks as an assumption but it is relevant to start by recalling that it is made, since any reference to atomic constitutions is foreign to classical thermodynamics." Today, no modern book on statistical mechanics makes that *assumption* explicitly. It is a universally accepted fact.

entropy. One must supplement this relationship with three critically important facts and assumptions. First, that there is a huge number of particles and an even “huger” number of microstates. Second, that all these states are equally likely i.e. have equal probability of occurrence, hence are equally likely to be visited by the system. Third, and most importantly, that at equilibrium, the number of *microstates* that are consistent with (or belonging to) the *macrostate* that we actually observe, is almost equal to the *total* number of possible microstates. We shall come back to these aspects of a physical system in Chapters 6 and 7.

With these further assumptions that would crystallize into a firm theory of statistical thermodynamics, the atomistic formulation of entropy has gained a decisive victory. The non-atomistic formulation of the Second Law is still being taught and applied successfully. There is nothing wrong with it except for the fact that it does not, and in principle cannot reveal the secrets ensconced in the concept of entropy.

Boltzmann’s heuristic relation between entropy and the logarithm of the total number of states¹⁹ did open the door to an understanding of the meaning of entropy. However, one needs to take further steps to penetrate the haze and dispel the mystery surrounding entropy.

There are several routes to achieve this end. I shall discuss the two main routes. One is based on the interpretation of entropy in terms of the extent of disorder in a system;²⁰ the second involves

¹⁹For simplicity and concreteness, think of N particles distributed in M cells. A full description of the state of the system is a detailed specification of which particle is in which cell.

²⁰The association of entropy with disorder is probably due to Bridgman (1941). Guggenheim (1949) suggested the term “spread” to describe the spread over a large number of possible quantum states. A thorough discussion of this aspect is given by Denbigh and Denbigh (1985).

the interpretation of entropy in terms of the missing information on the system.²¹

The first, the older and more popular route, has its origin in Boltzmann's own interpretation of entropy: a large number of states can be conceived of as having a large degree of disorder. This has led to the common statement of the Second Law of Thermodynamics that "Nature's way is to proceed from order to disorder."

In my opinion, although the order-disorder interpretation of entropy is valid in many examples, it is not always obvious. In a qualitative way, it can answer the question of *what* is the thing that changes in some spontaneous processes, but not in all. However, it does not offer any answer to the question of *why* entropy always increases.

The second route, though less popular among scientists is, in my opinion, the superior one. First, because *information* is a better, quantitative and objectively *defined* quantity, whereas order and disorder are less well-defined quantities. Second, information, or rather the missing information, can be used to answer the questions of *what* is the thing that changes in *any* spontaneous process. Information is a familiar word; like energy, force or work, it does not conjure up mystery. The measure of information is defined precisely within information theory. This quantity retains its basic meaning of *information* with which we are familiar in everyday usage. This is not the case when we use the concept of "disorder" to describe *what* is the thing that changes. We shall further discuss this aspect in Chapters 7 and 8. Information in itself does not provide an answer to the question of *why* entropy changes in this particular way. However, information unlike disorder, is defined in terms of probabilities

²¹Information theory was developed independently of thermodynamics by Claude Shannon in 1948. It was later realized that Shannon's informational measure is identical (up to a constant that determines the units) with Boltzmann's entropy.

and as we shall see, probabilities hold the clues to answering the question “*why.*”

For these reasons, we shall devote the next chapter to familiarizing ourselves with some basic notions of probability and information. We shall do that in a very qualitative manner so that anyone with or without a scientific background can follow the arguments. All you need is sheer common sense. Once you acquire familiarity with these concepts, the mystery surrounding entropy and the Second Law will disappear, and you will be able to answer both the questions: “What is the thing that is changing?” and “Why is it changing in this particular manner?”

